"Someone who insists upon seeing with perfect clearness before he decides, never decides."

Henri Amiel (1821-1881)

"There are no passengers on Spaceship Earth. We are all crew."

Marshall McLuhan (1911-1980)

"Nobody makes a greater mistake than he who does nothing because he could only do a little."

Edmund Burke (1729-1797)

Current Assignments ...

Office hours:
2-3 Tuesday &
3-4 Thursday

For today:

- Read Section 9.9

For Lecture 13 (February 26):

- Read Sections 10.1-10.4

Suggested Conceptual Exercises:

- Chapter 9: 43, 45, 47

Homework #2

- Due 11:00 AM, Thursday, February 14 – now!

Homework #3

- Handed out today, due 11:00 AM, Thurs, March 7

Writing Assignment #1

- Due 11:00 AM, Thursday, February 28

Tutorial #5

- Homework #1 will be returned and discussed

Review of Lecture 11

Textbook, Section 9.8

Ozone and ozone depletion

- What is ozone?
- What is happening to ozone?
- What causes ozone depletion?
- What will happen to ozone in the future?

Plan for Lecture 12

Textbook, Section 9.9

Climate Change

- The greenhouse effect
- Intergovernmental Panel on Climate Change
- The observations: greenhouse gases
- The observations: temperature
- Radiative forcing
- Human influence on climate
- Climate model predictions

Discussions on climate change are often heated… Why?

- There is a broad consensus in the scientific community that global warming is underway.
- The impacts of a steadily warming planet, with rising global average temperatures, are starting to be felt in many areas:
  - → Agricultural production, water availability, health, sea ice, the mere subsistence of low-lying islands and coastal zones
- Climate change has been attributed to an increase of greenhouse gases in the atmosphere.
  - → These gases are a result of activities in our everyday life: the use of energy from fossil fuels (coal, oil, gas), flying or driving, using electric equipment at home. Greenhouse gases also come from industrial processes, agricultural production and deforestation.
- The economic stakes are high on all sides
  - → The economic impact of climate change may be large.
  - → Taking measures to reduce emissions will affect economic activity.

THE GLOBE AND MAIL

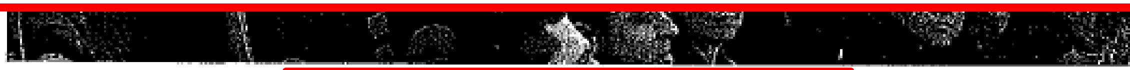
CANADA'S NATIONAL NEWSPAPER · THURSDAY, FEBRUARY 14, 2013

other. He devoted a substantial part of a speech outlining his second-term agenda to pledges to both reduce emissions and beef up U.S. energy security – but he gave no hints of where Canadian oil fits in.

His ambassador in Ottawa, David Jacobson, said that when Canadians can show progress on climate change, it has an impact on Americans' judgment of whether the energy-security benefits of oil-sands imports outweigh the environmental impact.

"It does," Mr. Jacobson said in an interview on Wednesday. "I think that there are an awful lot of folks who are trying to make up their minds, and trying to draw the right balance between these two things, who I think will be moved by progress."

Energy, Page 4



CAMPBELL CLARK

Canadian progress on combatting greenhouse-gas emissions would sway American views on Alberta's oil, U.S. Ambassador to Canada David Jacobson says.

In his State of the Union address on Tuesday night, U.S. President Barack Obama told the Congress that climate-change action is coming, one way or an-

other. He devoted a substantial part of a speech outlining his second-term agenda to pledges to both reduce emissions and beef up U.S. energy security – but he gave no hints of where Canadian oil fits in.

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Energy, Page 4

Civil rights protester Julian Bond, left, and Sierra Club Executive Director Michael Brune, second from left, gather with activists in front of the White House on Wednesday to protest the proposed Keystone XL pipeline. Both were later arrested for failure to disperse.

ANN HEISENFELT/THE ASSOCIATED PRESS

Some Definitions

Weather

- the fluctuating state of the atmosphere around us, characterized by the temperature, wind, precipitation, clouds and other weather elements

Climate

- the average weather in terms of the mean and its variability over a certain time-span and a certain area

"*Climate is what we expect, weather is what we get*."

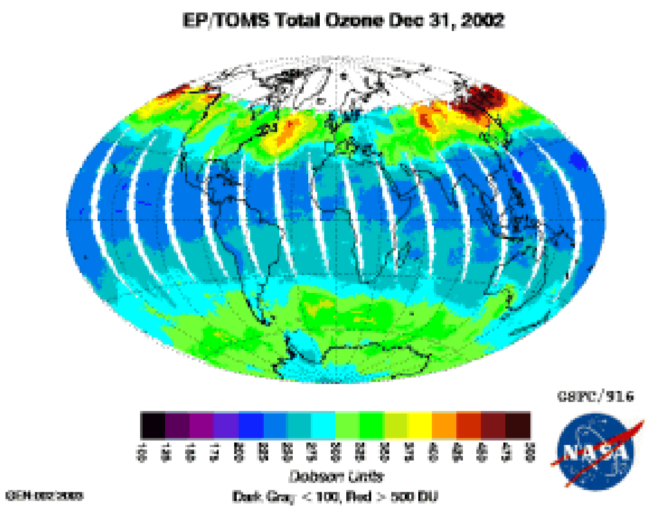
Mark Twain

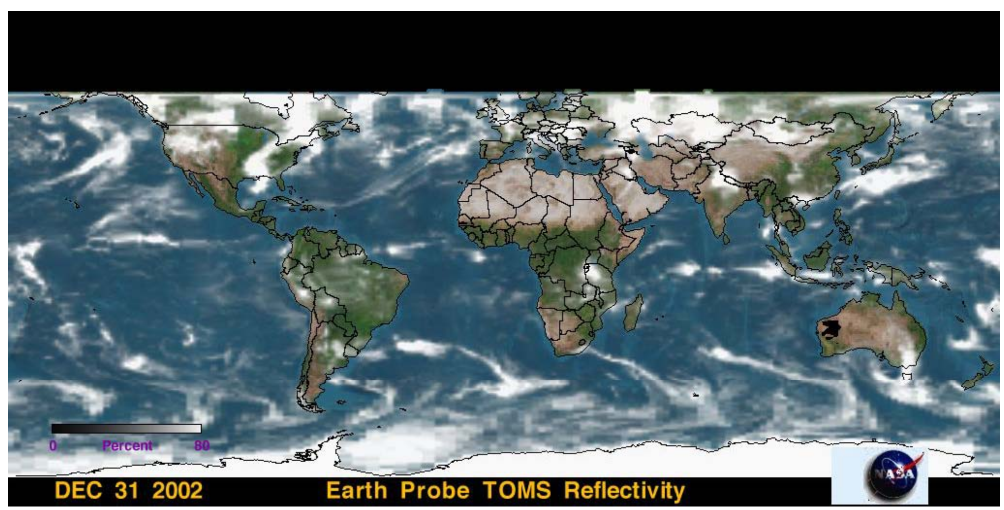
Climate change

- statistically significant variations of the mean state of the climate or of its variability, typically persisting for decades or longer

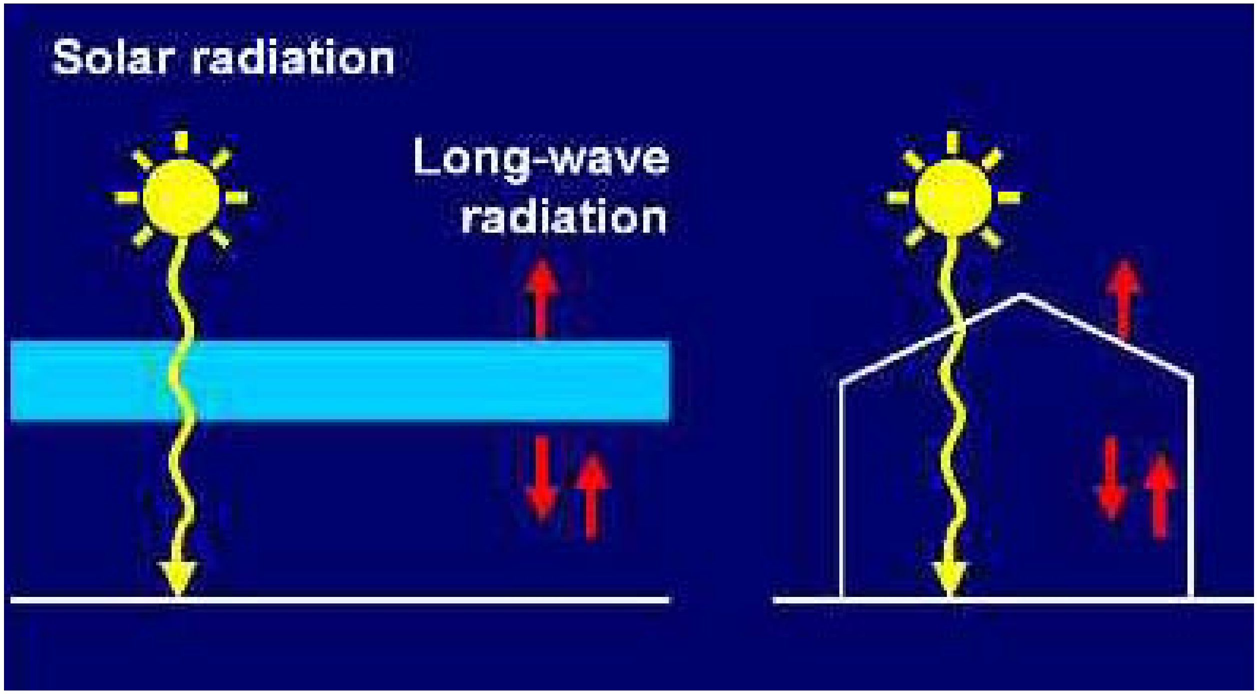
The Climate System

- The climate system is an interactive system forced or influenced by various external forcing mechanisms, the most important of which is the Sun.
- The atmosphere is the most unstable and rapidly changing part of the system.
- The climate of the Earth as a whole depends on factors that influence the radiative balance, such as for example, the atmospheric composition, solar radiation or volcanic eruptions.





The Greenhouse Effect



- Earth's temperature as seen from space (really the temperature of the upper atmosphere) is about -19°C.
- The average surface temperature is about 14°C.
- The 33°C difference is due to Earth's blanket of greenhouse gases; without them, the surface would also be about -19°C.

Earth’s Energy Budget with No GHGs

Textbook
Figure 9.36

Numbers are percentages

Earth’s Energy Budget With GHGs

This infrared loop, consisting of infrared radiation absorbed and reradiated by greenhouse gases, is what keeps Earth’s surface warmer than its upper atmosphere.

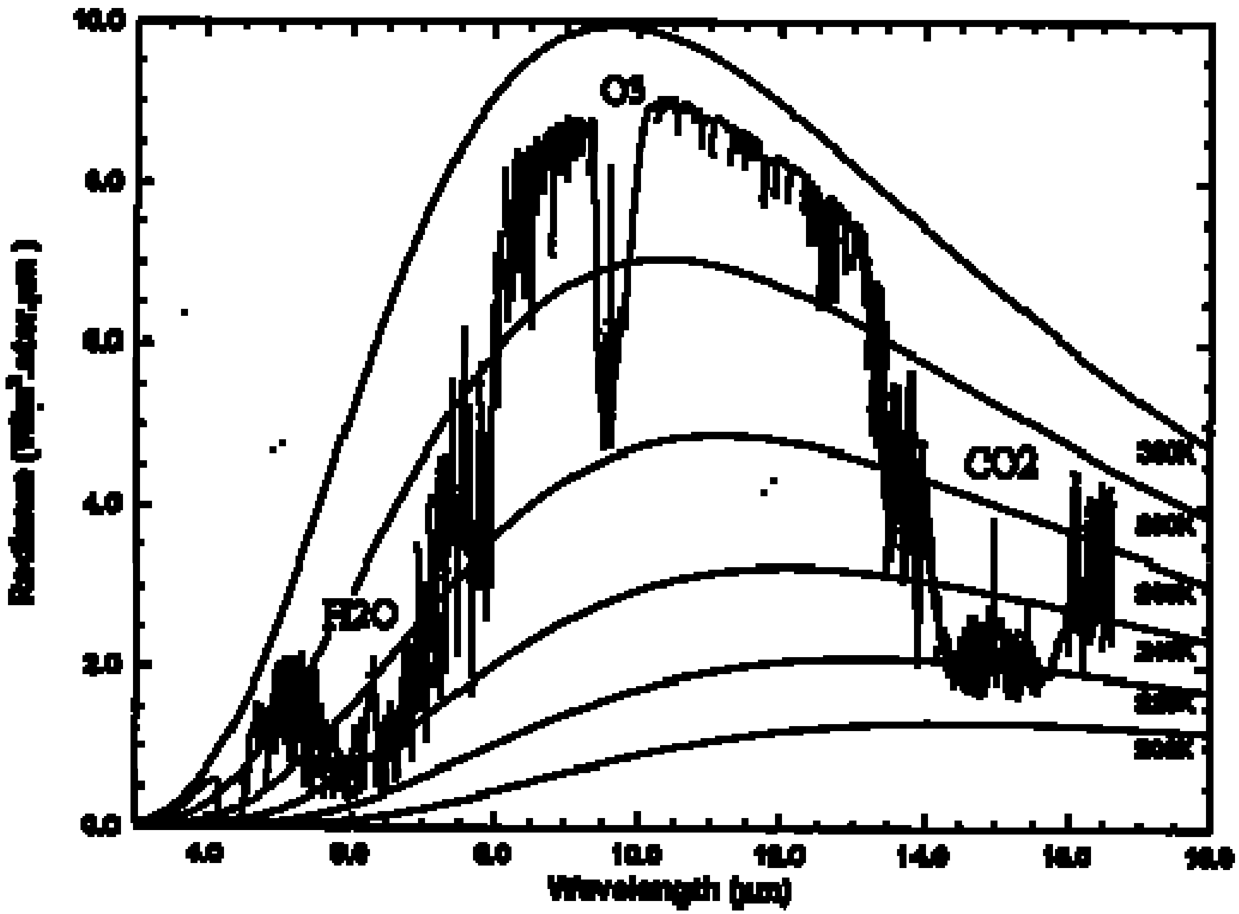
This greenhouse effect is natural, and has existed for many millions of years.

Textbook Figure 9.37

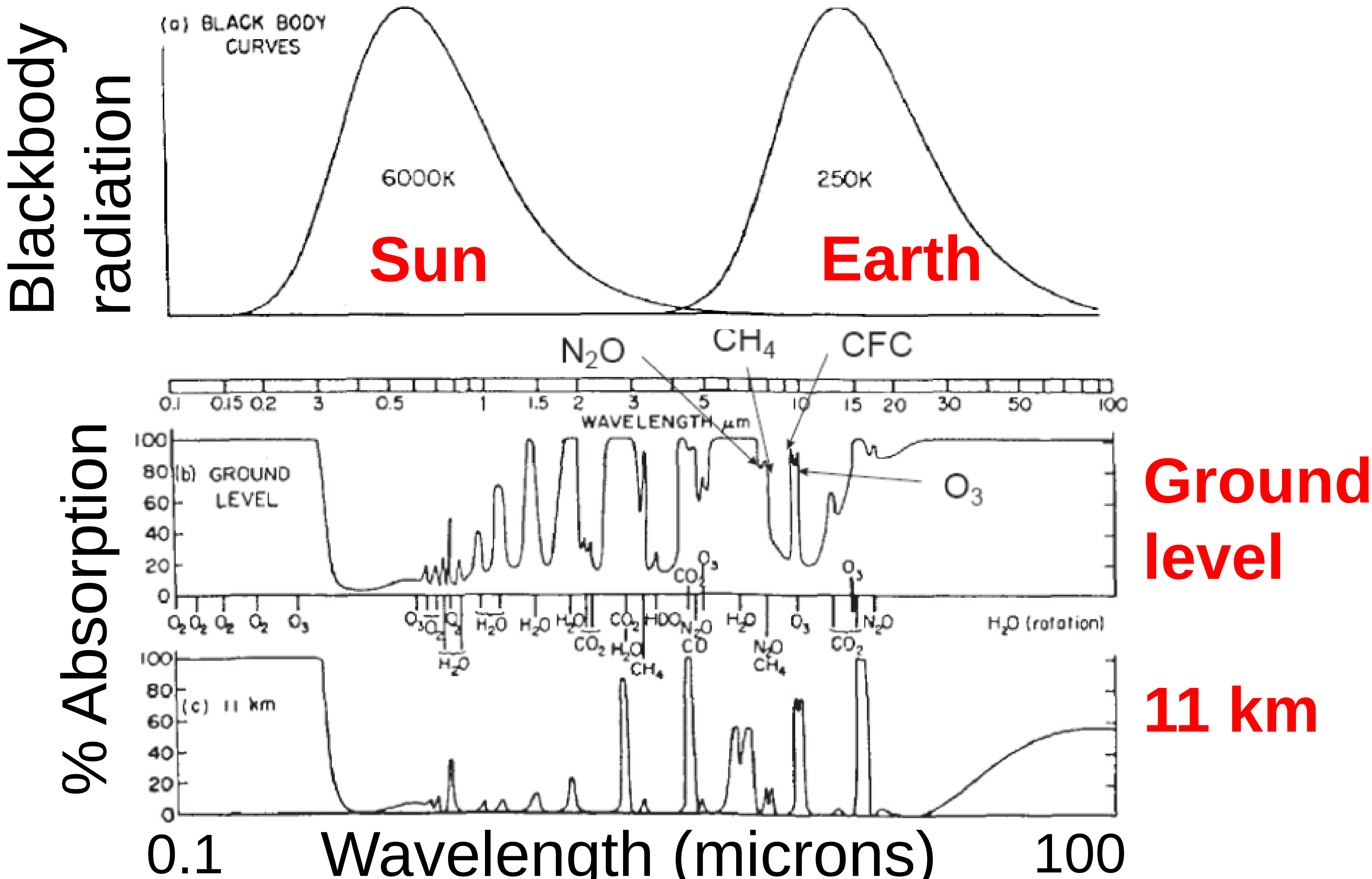
Numbers are percentages

Thermal (IR) Radiation Spectrum

- This figure shows the infrared radiation emitted by the Earth and its atmosphere.
- Note the underlying blackbody emission and the absorption due to gases.
- CO_2 is uniformly mixed in the atmosphere, while H_2O and O_3 vary in space and time.



Atmospheric Absorption

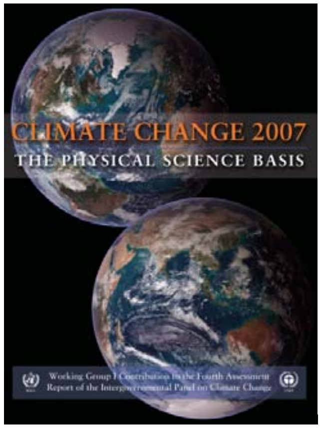


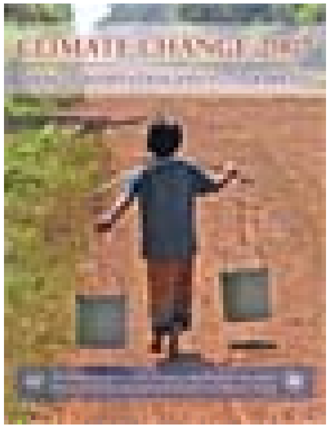
The Scientific Basis: IPCC Reports

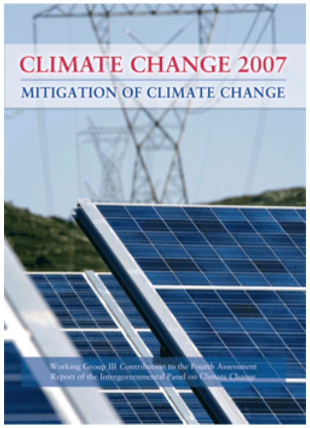
The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the WMO and UNEP to assess scientific, technical and socio-economic information relevant for the understanding of climate change, its potential impacts, and options for adaptation and mitigation.

- Four reports have been published: 1990, 1995, 2001, 2007
- The Fourth Assessment Report (AR4) was released in 2007
  - → Working Group I - The Physical Science Basis
  - → Working Group II - Impacts, Adaptation, and Vulnerability
  - → Working Group III - Mitigation of Climate Change
- Oslo, 10 December 2007 - The IPCC and Al Gore were awarded of the Nobel Peace Prize ***"for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change".***

IPCC Documentation







IPCC Homepage

- www.ipcc.ch

Summary for Policymakers (SPM), 18 pages,
from Working Group I Report "The Physical Science Basis"

- www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

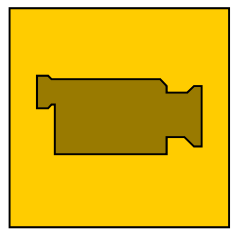
I encourage you tread the Science Summary for Policymakers at the link above. I will add this to today’s webpage.

Greenhouse Gases

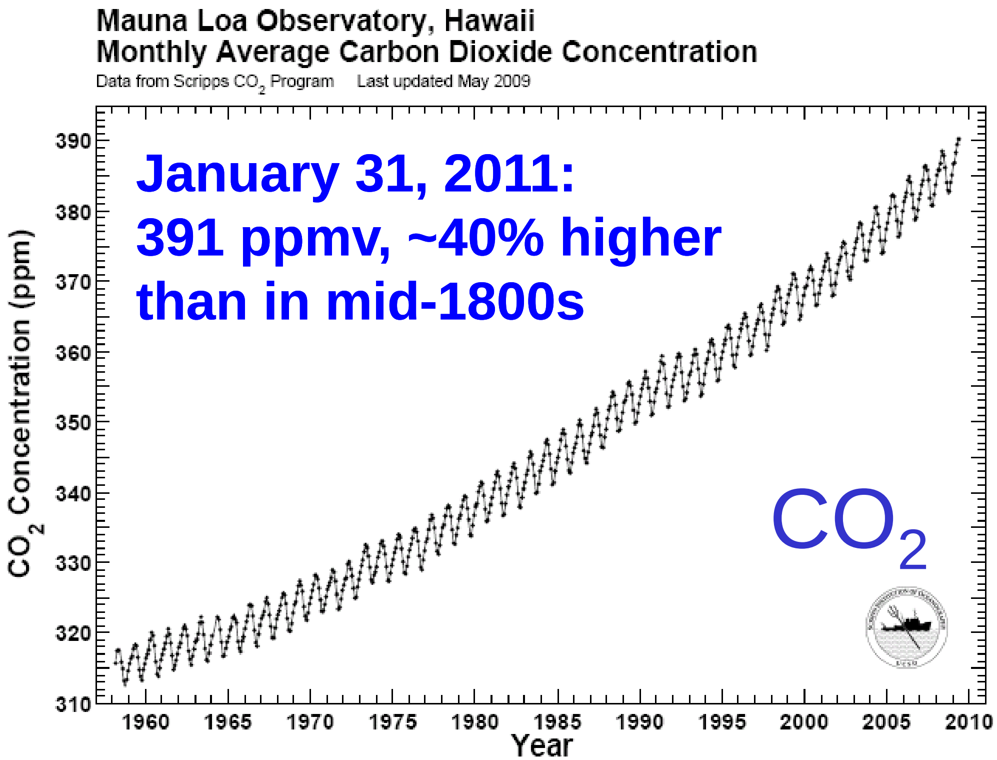
Textbook Figure 9.42

- **Water vapour (H_2O)**
  - → most common greenhouse gas
  - → increases as surface temperature rises
- **Carbon dioxide (CO_2)**
  - → released by plant and animal life, decay, and burning of fuels
  - → removed by plant photosynthesis and absorption by the oceans
- **Methane (CH_4)**
  - → very effective at trapping heat - powerful greenhouse gas
  - → wetlands, rice paddies, animal digestion, fossil fuel extraction, decaying garbage
- **Nitrous oxide (N_2O)**
  - → soils and the oceans, some from burning fossil fuels and fertilizer use
- **Ozone (O_3)**
  - → most ground level ozone is from chemical reactions involving pollutants
- **Halocarbons**
  - → chemicals containing bromine, chlorine, or fluorine, and carbon
  - → extremely powerful greenhouse gases

Infrared Absorption by CO_2



The “Keeling Curve”



Charles David Keeling began collecting data at Mauna Loa, at 3400 m elevation, in March, 1958.

The Mauna Loa atmospheric CO_2 concentration measurements constitute the longest, continuous record of atmospheric CO_2 available in the world.

http://scrippsco2.ucsd.edu/

http://www.mlo.noaa.gov/programs/coop/scripps/co2/co2.html

Observed Fact: The CO_2 (and CH_4, N_2O,…) content of the Earth’s atmosphere is steadily increasing due to the burning of fossil fuels which releases the trapped carbon into the atmosphere.

The Carbon Dioxide Record

IPCC 2007: Global CO_2 increased from a pre-industrial value of ~280 ppm to 379 ppm in 2005. Range over the last 650,000 years is 180 to 300 ppm (from ice cores).

(a) Direct measurements of atmospheric CO_2.

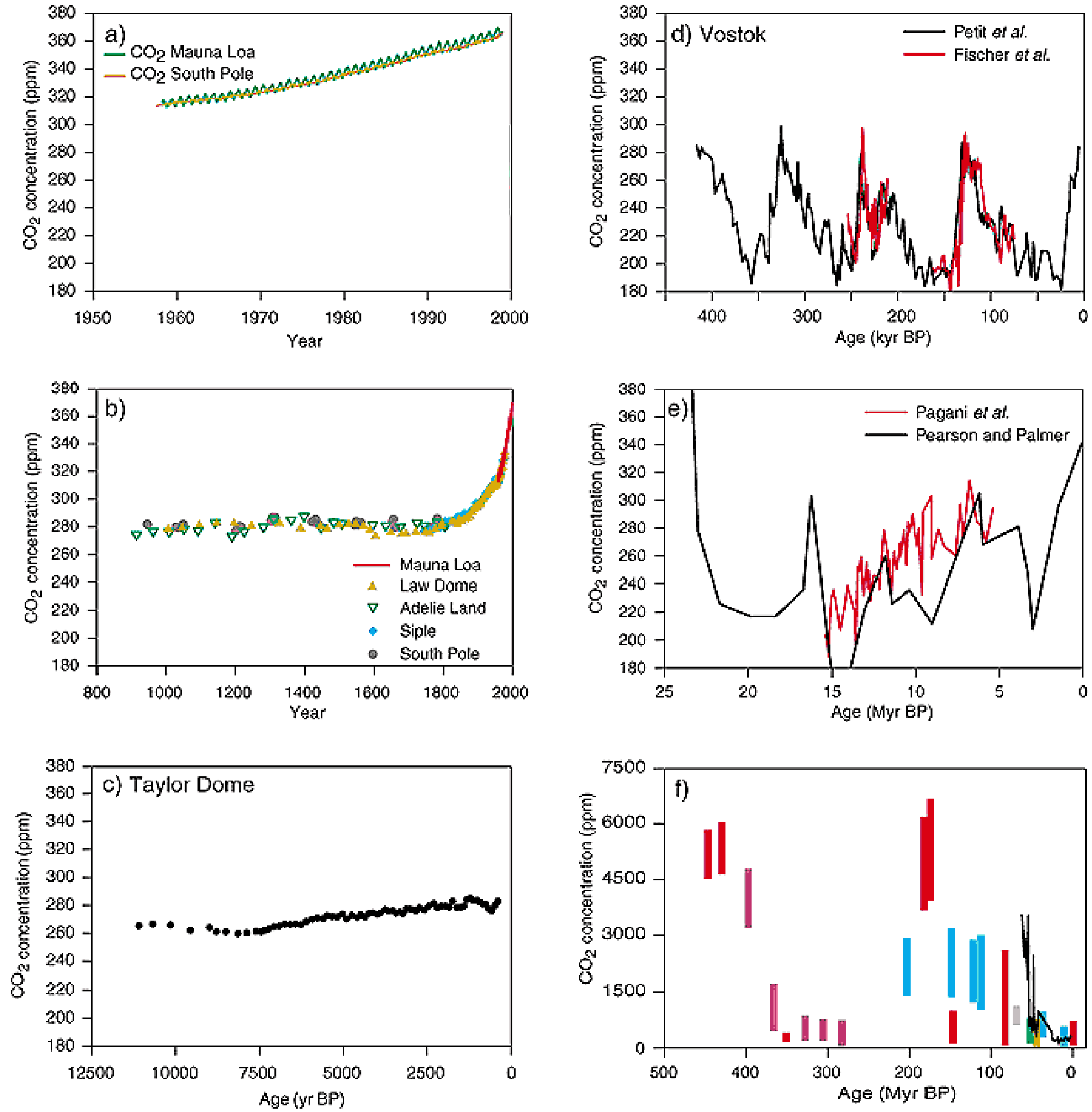
(b) CO_2 in Antarctic ice cores, with Mauna Loa data for comparison.

(c) CO_2 in the Taylor Dome Antarctic ice core.

(d) CO_2 in the Vostok Antarctic ice core.

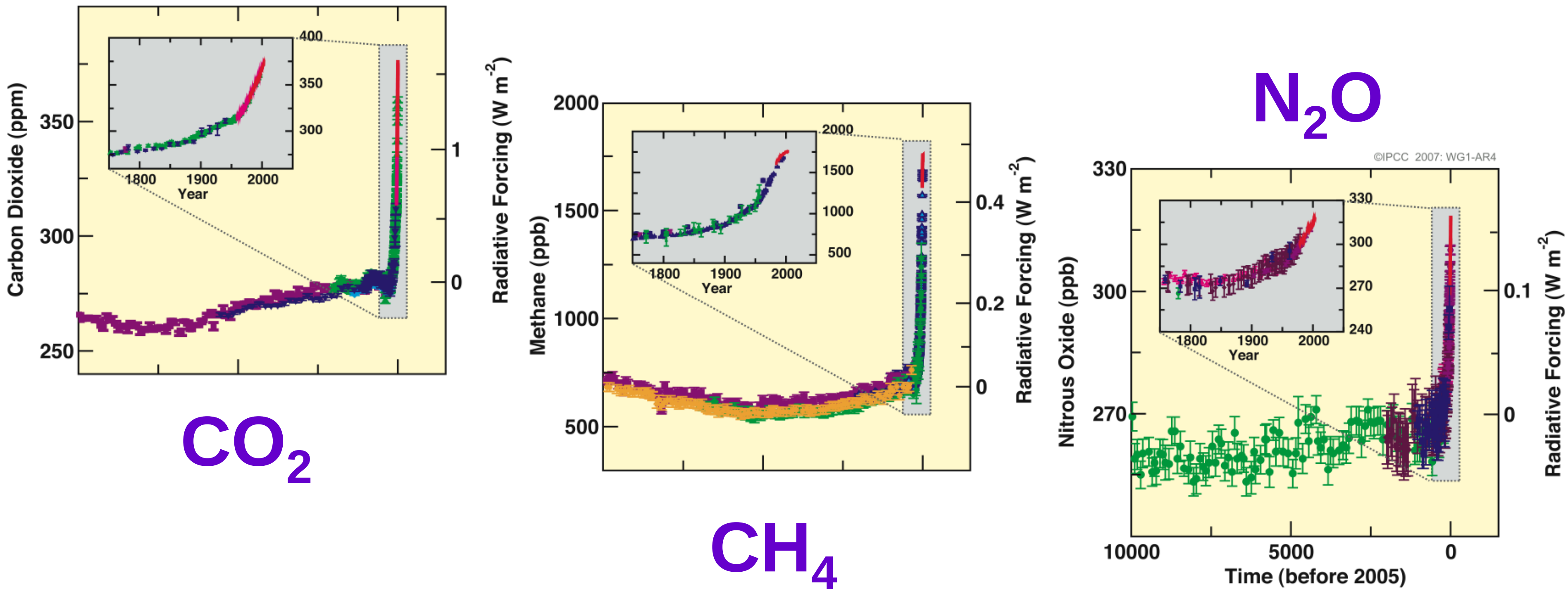
(e) and (f) Geochemically inferred CO_2.

(IPCC 2001, Figure 3.2)



GHGs: CO_2, CH_4, N_2O

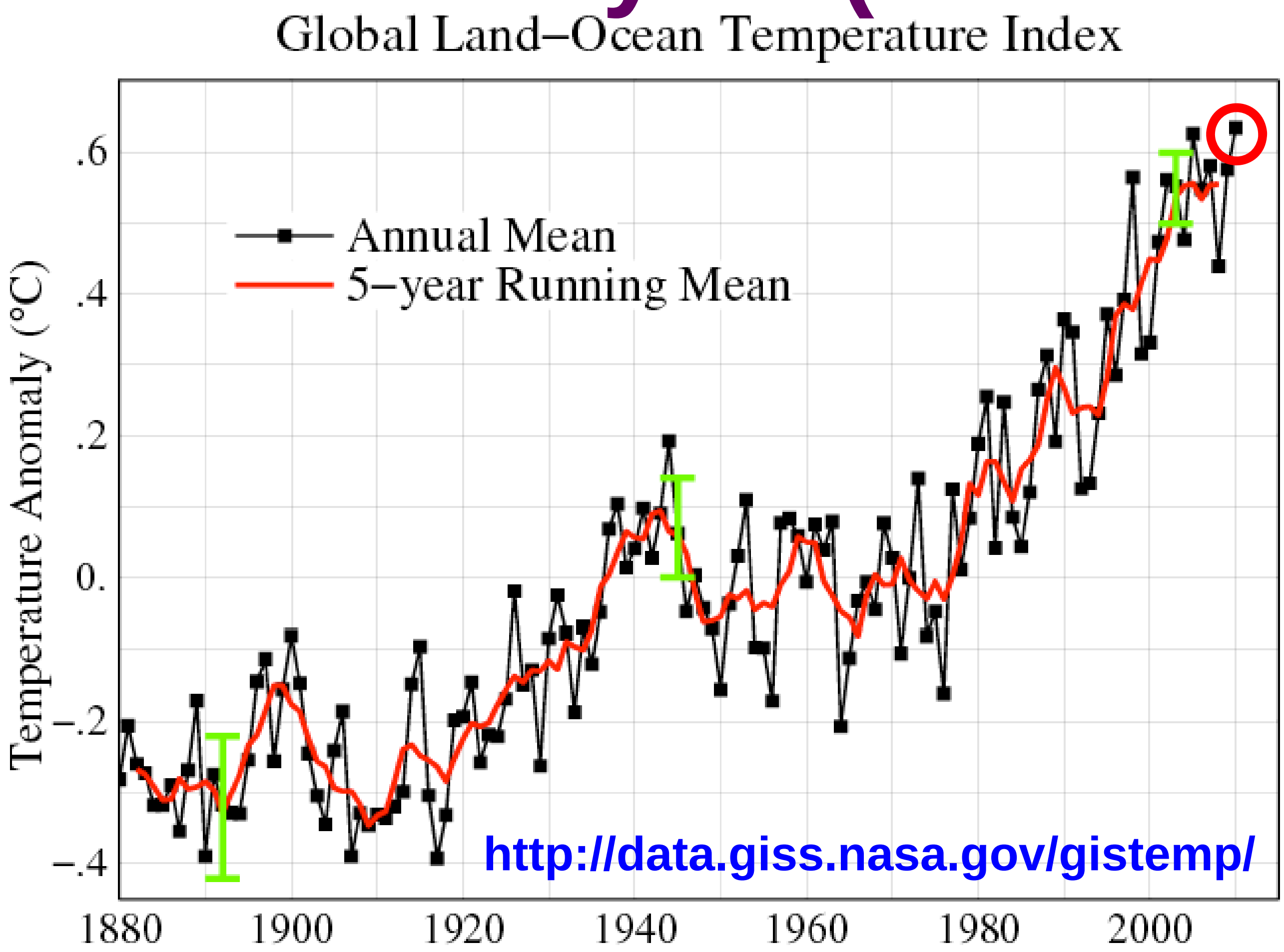
Atmospheric concentrations over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right-hand axes of the large panels.



Observed Changes in Temperature

- IPCC 2007: The **100-year** linear **trend** (1906–2005) is **0.74°C**, and is larger than earlier values because of record warmth over the previous decade.
  - → IPPC 2001: Global average surface temperature increased by **0.6°C** for 1901-2000.
  - → IPCC 1995: **0.15°C** from pre-industrial values
- Most of the increase in global temperature has occurred in two distinct periods: 1910 to 1945 and since 1976 (0.15°C/decade).
- Recent warming is greater over land than over oceans.

NASA GISS Surface Temperature Analysis (GISTEMP)



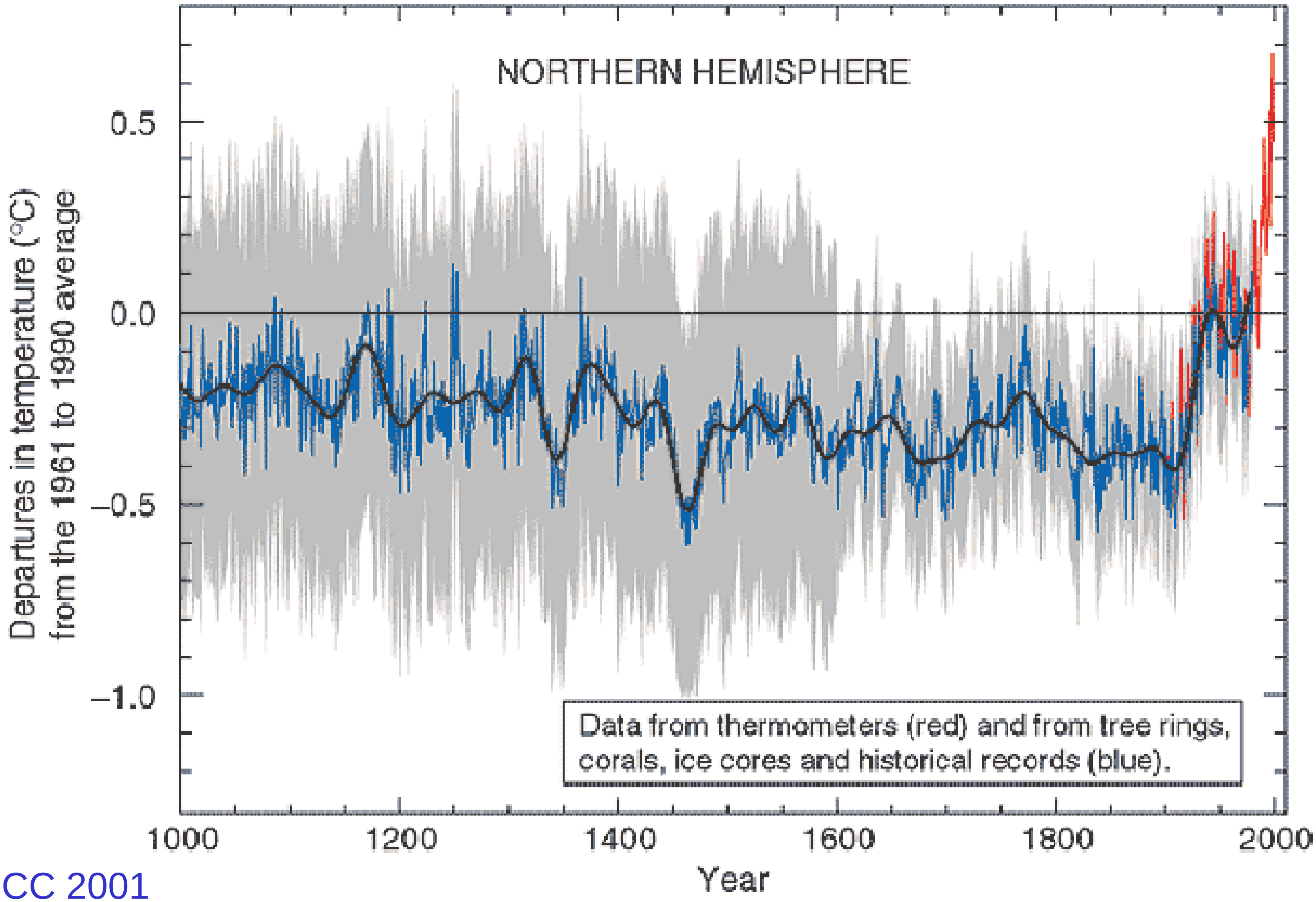
NASA Top 10

2010
2005 **tied**
1998
2003
2002
2009
2006
2007
2004
2001

- **2010, tied for warmest year globally on record (announced January 12, 2011)**
- **19 countries set record highs in 2010; only one set a record low**
- **2001-2010 was the warmest decade in recorded history**
- **2010 was the wettest year globally since 1900**

Courtesy of Tom Pedersen, PICS
CMOS Lecture, 2011

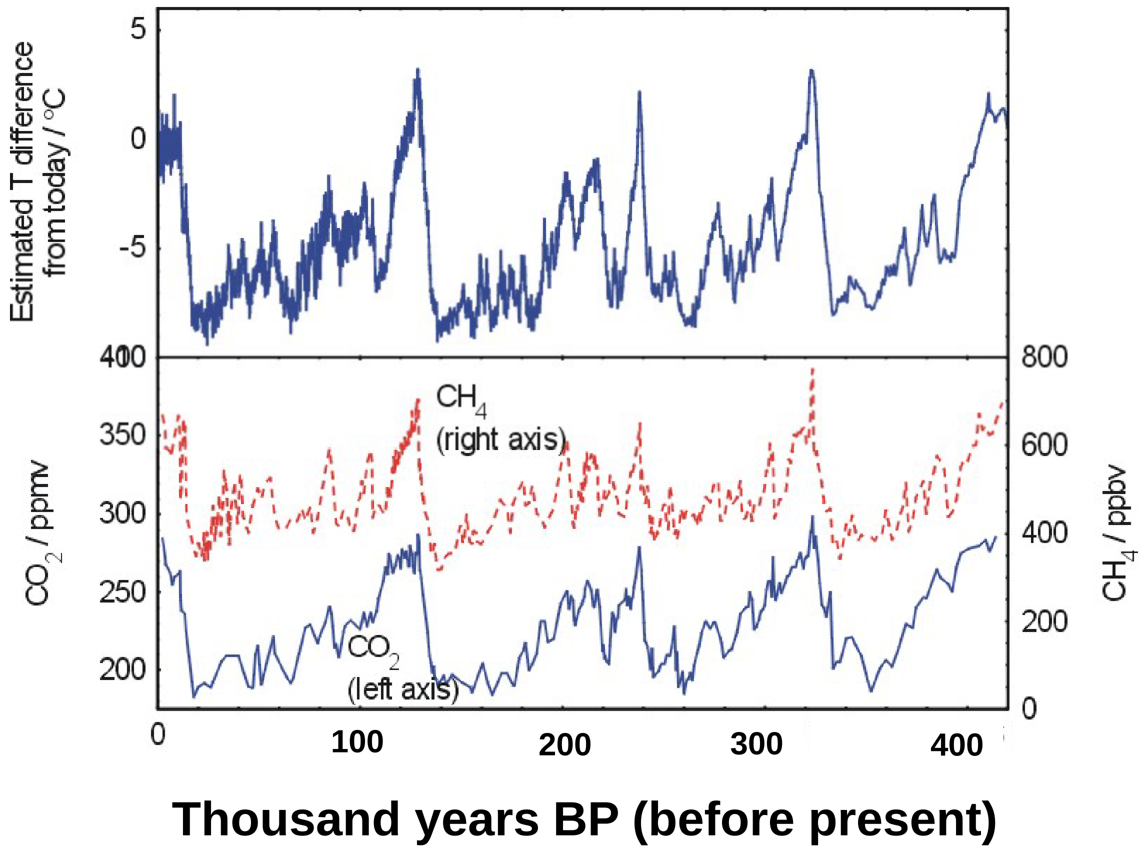
Surface Temperature Trends - 1000 yrs



IPCC 2001

Observed Changes in Temperature

Over 400,000 years



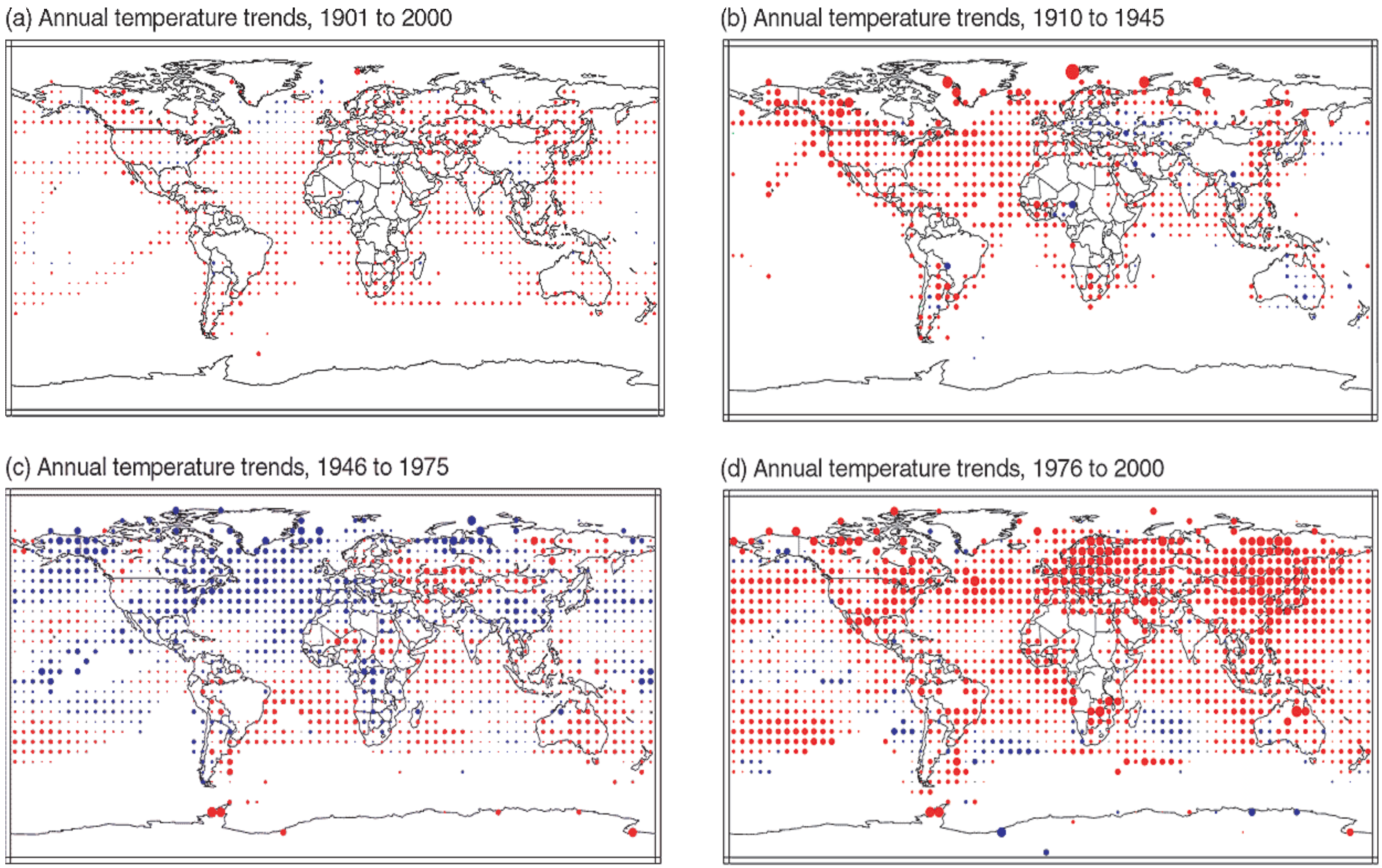
E. Wolff, British Antarctic Survey

Series of ice ages

Reasons for temperature swings:

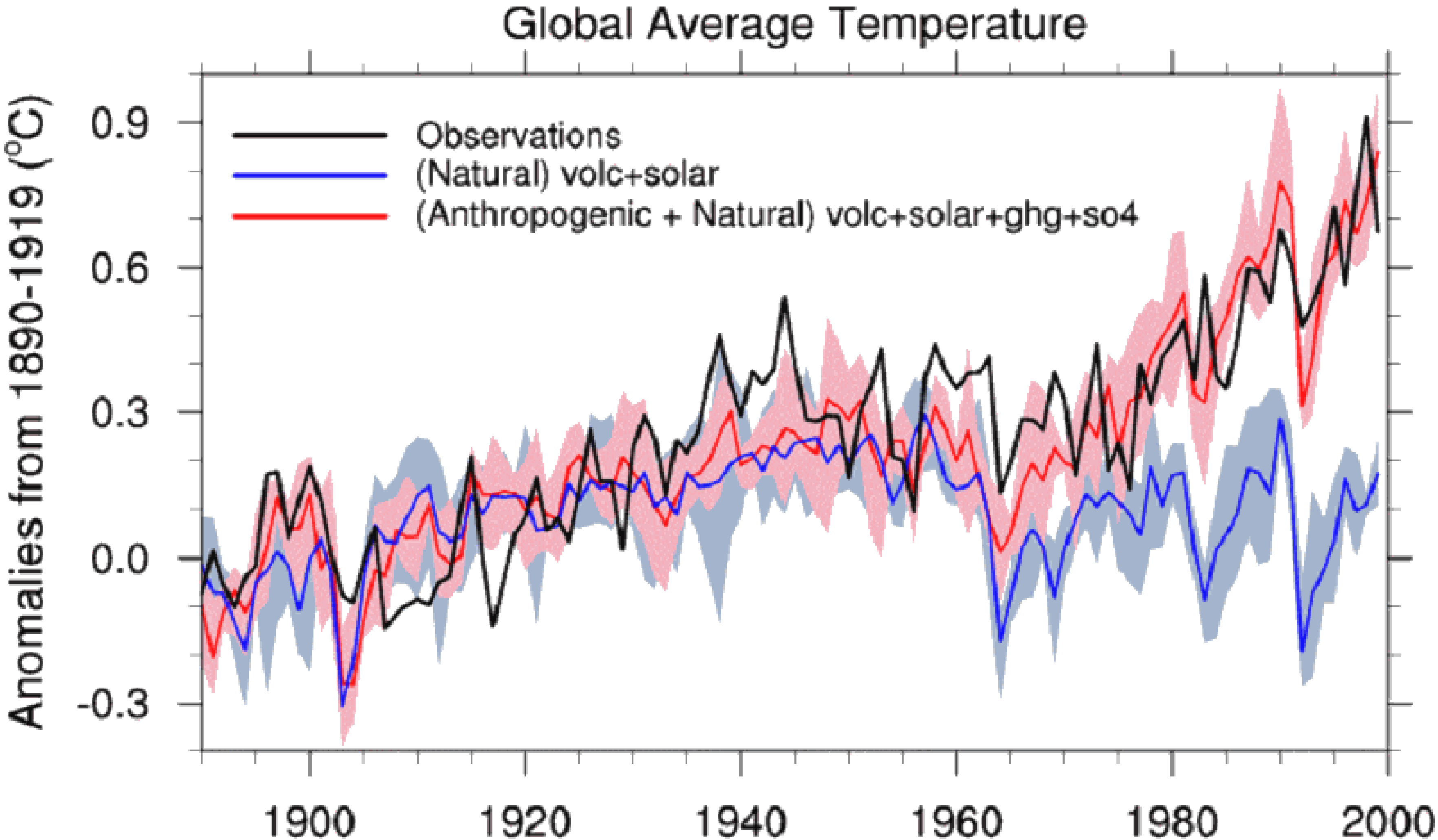
Changes in Earth's orbit or tilt, amplified by changes in greenhouse gases?

Surface Temperature Trends - 100 yrs



The size of each circle reflects the size of the trend that it represents. Red = positive trend. Blue = negative trend.
(IPCC 2001, Figure 2.9)

Modelling Surface Temperature Trends

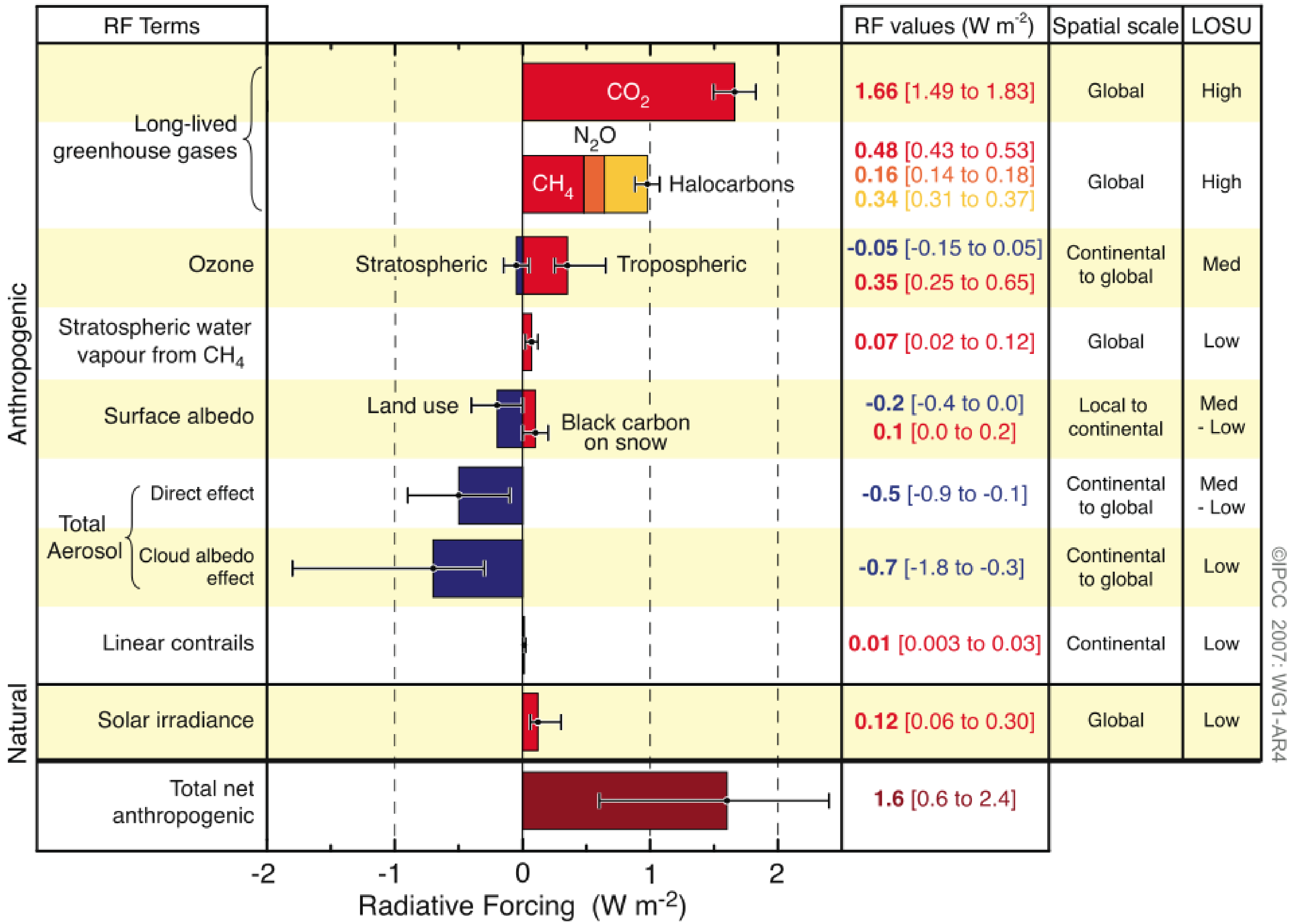


NCAR Ensemble Simulations
From presentation by Rick Anthes, UCAR Meeting, Boulder, CO, 7 October 2003

Radiative Forcing

- Any factor that alters the radiation received from the Sun or lost to space, or that alters the redistribution of energy within the atmosphere and between the atmosphere, land, and ocean, can affect climate.
- A change in the net radiative energy available to the global system is called a radiative forcing (W m^{-2}). Causes include:
  - →Changes in the concentrations of radiatively active species (e.g., CO_2, aerosols) – the amount of radiative forcing depends on the size of the change, the radiative properties of the gas, and the concentrations of other greenhouse gases
  - →Changes in the solar irradiance incident upon the planet
  - →Other changes that affect the radiative energy absorbed by the surface (e.g., changes in surface reflection properties)
- Positive radiative forcings warm Earth's surface and lower atmosphere. Negative radiative forcings tend to cool them.

IPCC 2007 Figure SPM.2
Global Average Radiative Forcing (RF)



Climate Sensitivity Parameter

- The climate sensitivity parameter λ (not wavelength here!) is defined as the global mean surface temperature response ΔT_s to the radiative forcing ΔF:

$$\Delta T_s = \lambda \, \Delta F$$

- In one-dimensional radiative-convective models, wherein the concept was first initiated, λ is about 0.3 K / (Wm^{-2}).
- If we assume 2.5 W m^{-2} as the total radiative forcing from increases in greenhouse gases since 1885, we get

ΔT_s = 0.8°C [vs. observed change of 0.74°C]

- Simulations with GCMs (global circulation models) give λ from 0.3 to 1.4 K / (Wm^{-2}).

Global Warming Potentials

- Global warming potential (GWP) is a measure of the relative radiative effect of a given substance compared to CO_2 over a chosen time period.

Definition (IPCC 1998):

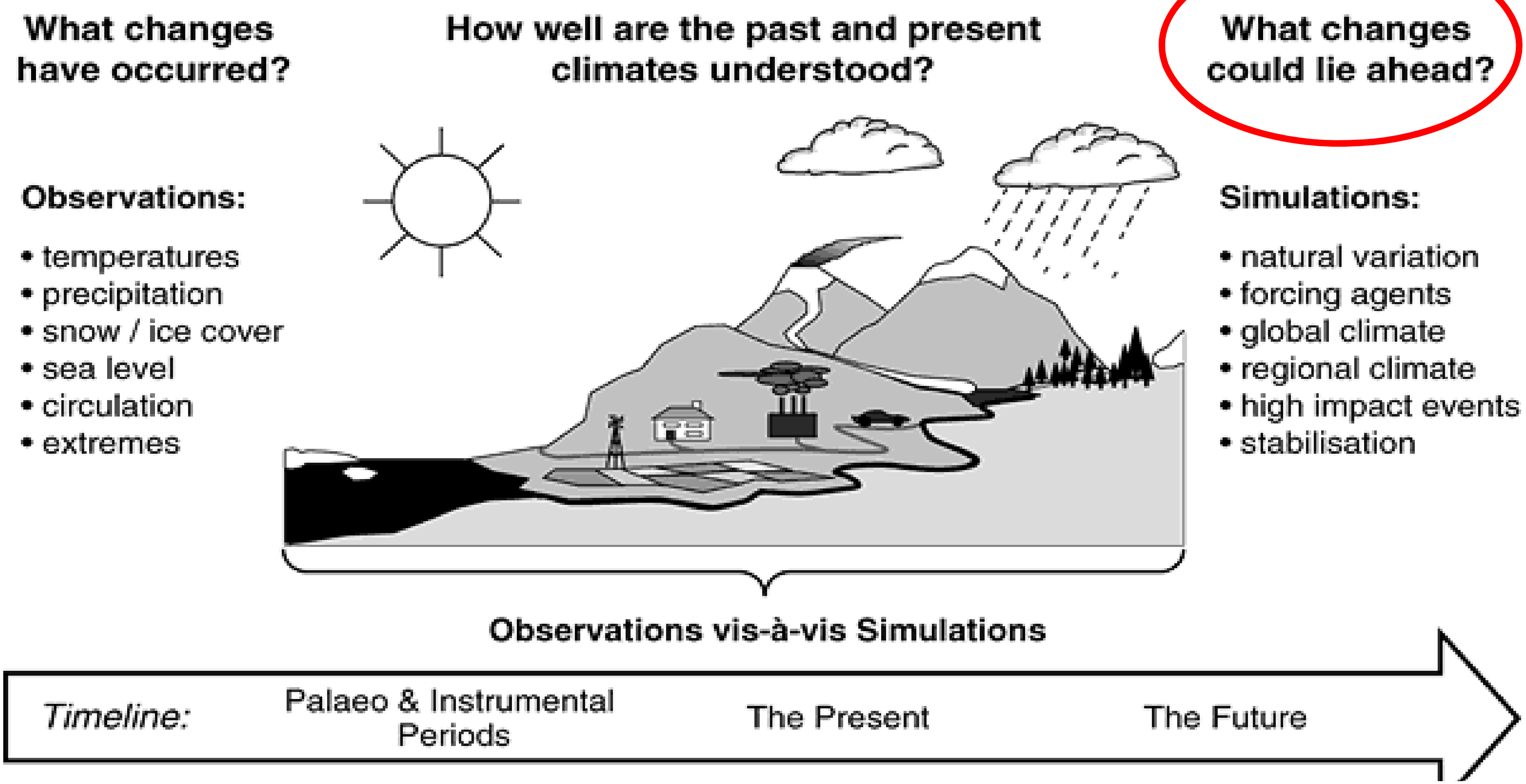
GWP = time-integrated warming effect due to an instantaneous release of unit mass (1 kg) of a given green-house gas in today's atmosphere, relative to the effect of CO_2.

- This concept was created to enable decision makers to evaluate options to evaluate future emissions of various greenhouse gases without having to perform complex model calculations.

Greenhouse Gases: Abundances, Lifetimes, and GWPs

Chemical species	Formula	Abundance ppt 1998	1750	Life-time (yr)	100-yr GWP
Carbon Dioxide	CO_2 (ppm)	365	280	5-200	1
Methane	CH_4 (ppb)	1745	700	8.4/12	23
Nitrous oxide	N_2O (ppb)	314	270	120/114	296
Perfluoromethane	CF_4	80	40	>50000	5700
Perfluoroethane	C_2F_6	3.0	0	10000	11900
Sulphur hexafluoride	SF_6	4.2	0	3200	22200
HFC-23	CHF_3	14	0	260	12000
HFC-134a	CF_3CH_2F	7.5	0	13.8	1300
Important greenhouse halocarbons under Montreal Protocol and its Amendments					
CFC-11	$CFCl_3$	268	0	45	4600
CFC-12	CF_2Cl_2	533	0	100	10600
CFC-13	CF_3Cl	4	0	640	14000
Carbon tetrachloride	CCl_4	102	0	35	1800
Methyl chloroform	CH_3CCl_3	69	0	4.8	140
HCFC-22	CHF_2Cl	132	0	11.9	1700
HCFC-142b	CH_3CF_2Cl	11	0	19	2400
Halon-1211	CF_2ClBr	3.8	0	11	1300
Halon-1301	CF_3Br	2.5	0	65	6900
Other chemically active gases directly or indirectly affecting radiative forcing					
Tropospheric ozone	O_3 (DU)	34	25	0.01-0.05	-
Tropospheric NO_x	$NO + NO_2$	5-999	?	<0.01-0.03	-
Carbon monoxide	CO (ppb)	80	?	0.08 - 0.25	-
Stratospheric water	H_2O (ppm)	3-6	3-5	1-6	-

Key Questions About the Climate System



IPCC 2001, TS Figure 1

Is Earth's Climate Changing?

Yes.

Based upon observations of:

- temperature (atmosphere and ocean)
- precipitation and atmospheric moisture
- snow cover, glaciers, extent of land and sea ice
- sea level
- patterns in atmospheric and oceanic circulation
- extreme weather and climate events
- overall features of the climate variability

Some Examples (IPCC 2007)

- Observations since 1961 show that the average **temperature of the global ocean has increased** to depths of at least 3000 m.
- Mountain **glaciers and snow cover have declined**.
- Global average **sea level rose at 1.8 mm/year** from 1961 to 2003.
- Average **Arctic temperatures increased** at almost twice the global average rate in the past 100 years.
- Satellite data since 1978 show that annual average **Arctic sea ice extent has shrunk** by 2.7% / decade (7.4% / decade in summer).
- Long-term trends from 1900 to 2005 have been observed in **precipitation amount** over many large regions.
- More **intense and longer droughts** have been observed over wider areas since the 1970s, particularly in tropics and subtropics.
- There is observational evidence for an **increase of intense tropical cyclone activity** in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures.

Causes of Climate Change

- Increasing atmospheric concentrations of greenhouse gases
- Increasing atmospheric concentrations of aerosols (microscopic airborne particles or droplets)
- Land surface properties
- Variations in solar activity

Human Influence on Climate - 1

IPCC 1995: *"the balance of evidence suggests that there is a* ***discernible*** *human influence on global climate"*

IPCC 2001 (TAR): *"In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is* ***likely*** *to have been due to the increase in greenhouse gas concentrations."*

IPCC 2007 (AR4): *"Most of the observed increase in globally averaged temperatures since the mid-20th century is* ***very likely*** *due to the observed increase in anthropogenic greenhouse gas concentrations. This is an advance since the TAR's conclusion that "most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations". Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns."*

Human Influence on Climate - 2

The *attribution* of climate change to anthropogenic causes involves statistical analysis and the careful assessment of multiple lines of evidence to demonstrate, within a pre-specified margin of error, that the observed changes are:

- unlikely to be due entirely to internal variability;
- consistent with the estimated responses to the given combination of anthropogenic and natural forcing; and
- not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings.

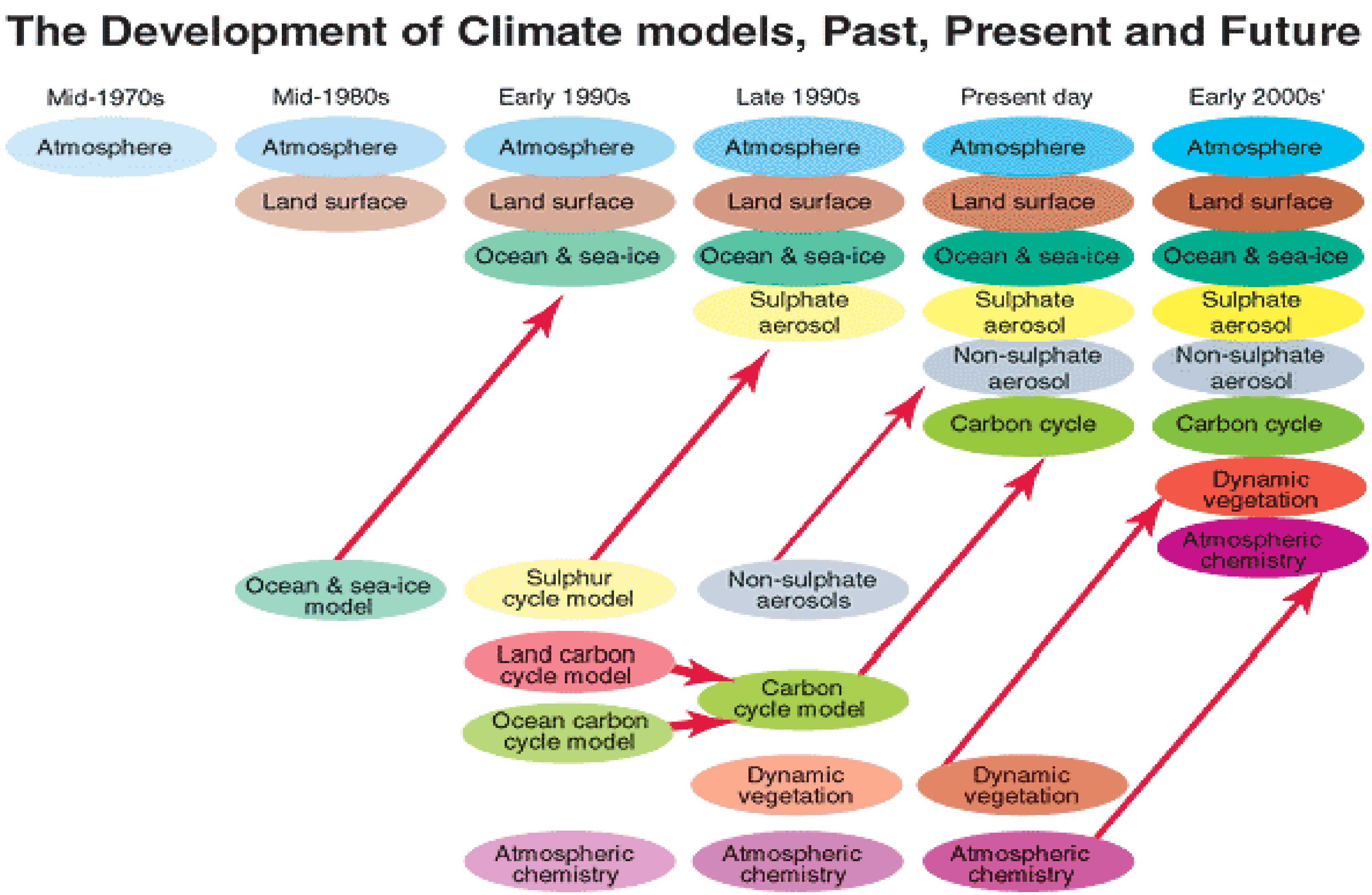
Remaining Uncertainties

- Simulating and attributing observed temperature changes at smaller scales.
  - → On these scales, natural climate variability is relatively larger, making it harder to distinguish changes expected due to external forcings.
- Simulating changes in atmospheric circulation.
  - → Anthropogenic forcing is likely to have contributed to changes in wind patterns, affecting extra-tropical storm tracks and temperature patterns in both hemispheres.
  - → However, the observed changes in the Northern Hemisphere circulation are larger than simulated in response to 20^{th} century forcing change.
- Reconstructions of solar and volcanic forcing, which are based on proxy or limited observational data for all but the last two decades.
- Cloud feedbacks remain a large source of uncertainty.

Climate Models

- Used to simulate climate response to different scenarios
- Based on physical laws represented by equations that are solved using a three-dimensional grid over the globe
- Major components of the climate are represented in sub-models (atmosphere, ocean, land surface, cryosphere, biosphere), along with processes between them
- Typical resolutions are a few 100 km in the horizontal and $\leq$ 1 km in the vertical
- Equations typically solved every half hour
- For processes that take place on much smaller spatial scales than the model grid, their average effects are approximated by using physically based relationships with the larger-scale variables (parameterization).

Development of Climate Models

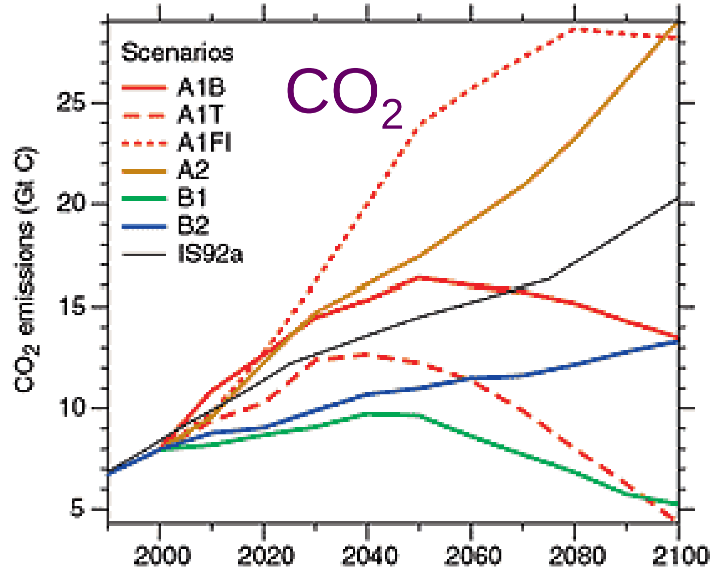


Climate Model Projections

Emissions Scenarios of Special Report on Emissions Scenarios (SRES)

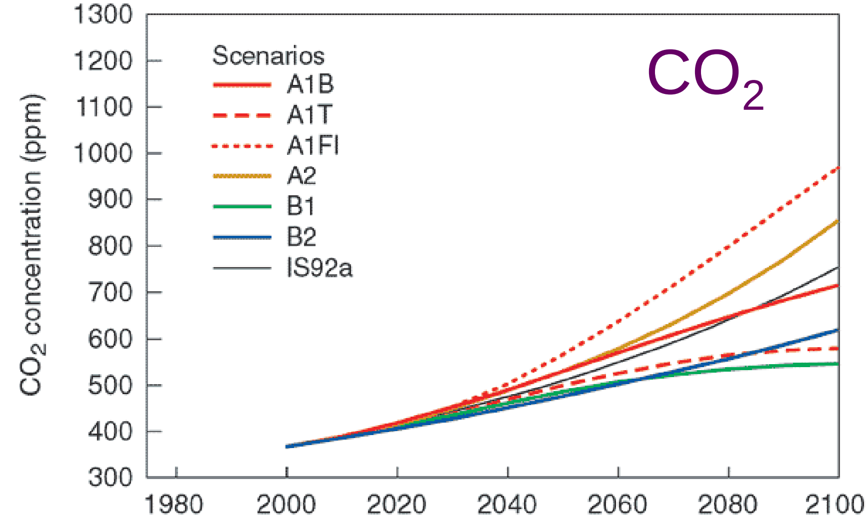
- A1 - rapid economic growth, global population peaks in mid-century and declines thereafter, and rapid introduction of new efficient technologies
  - → **A1FI** - fossil intensive **("worst case")**
  - → A1T - non-fossil energy sources
  - → A1B - a balance across all sources
- A2 - very heterogeneous world, self-reliance and preservation of local identities, continuously increasing population, fragmented economic development
- **B1** - convergent world with same global population as in A1, but with rapid change toward service and information economy, with reductions in material intensity and introduction of clean resource-efficient technologies **("best case")**
- B2 - emphasis on local solutions to economic, social and environmental sustainability, continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in A1 and B1

Step 1: Projected GHG Emissions



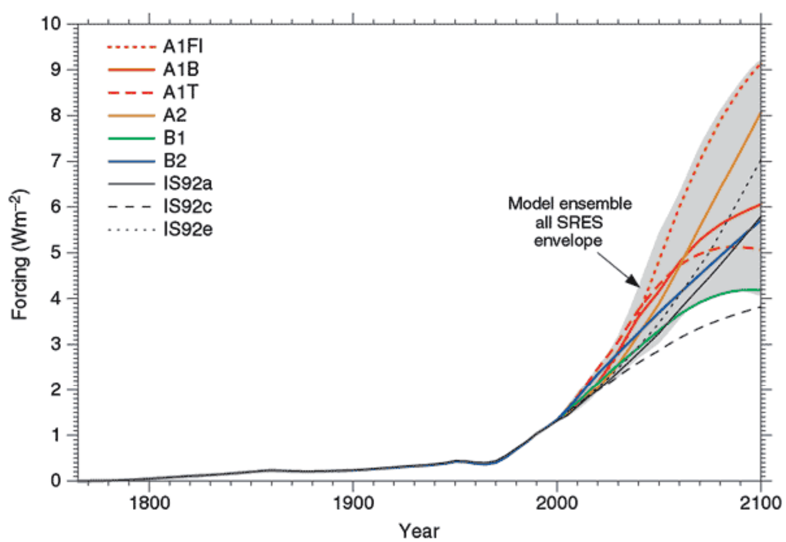
IPCC 2001 TS, Figure 17

Step 2: Resulting Atmospheric GHG Concentrations



IPCC 2001 TS, Figure 18

Step 3: Resulting Radiative Forcing



IPCC 2001, Figure 9.13a

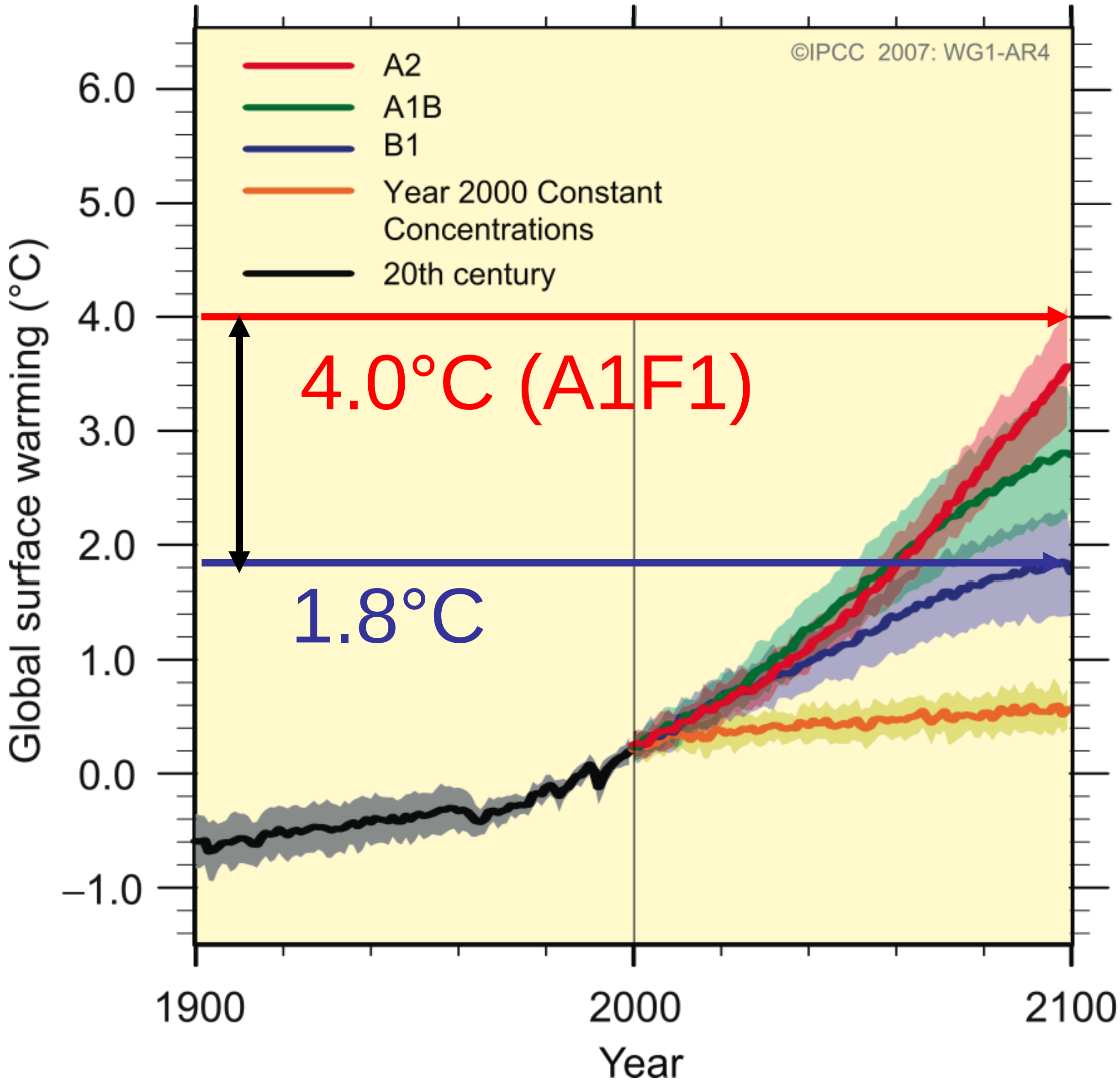
Estimated historical anthropogenic radiative forcing to 2000 followed by radiative forcing for the six SRES scenarios. The values are based on the radiative forcing for a doubling of CO_2 from seven AOGCMs.

Step 4 - Resulting Temperatures

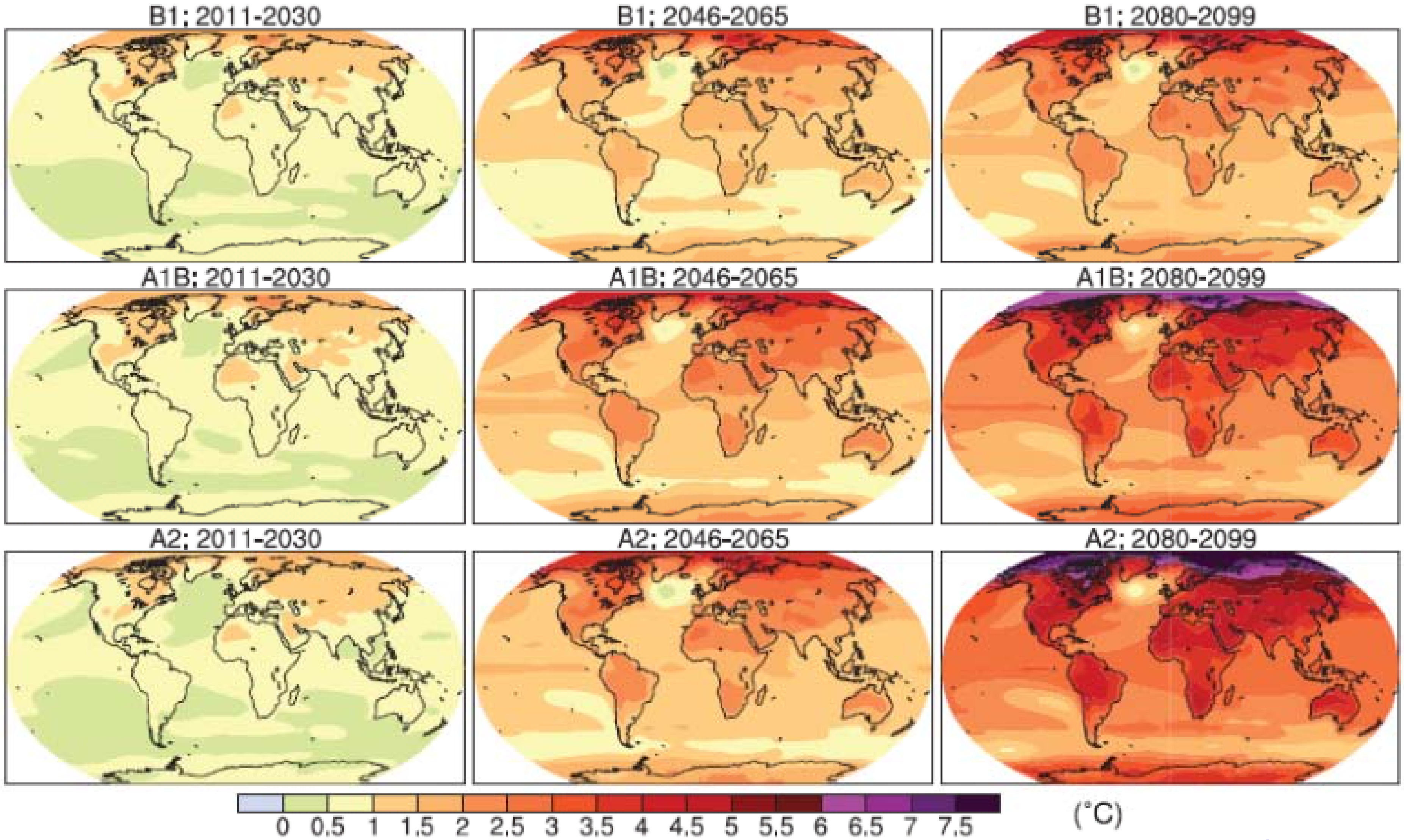
Multi-model global averages of surface warming, relative to 1980-1999.

Shading indicates the range of individual model annual averages (±1 standard deviation).

IPCC 2007
Figure SPM.5



Projected Temperature Changes



IPCC 2007 Figure 10.8

Figure 10.8. *Multi-model mean of annual mean surface warming (surface air temperature change, °C) for the scenarios B1 (top), A1B (middle) and A2 (bottom), and three time periods, 2011 to 2030 (left), 2046 to 2065 (middle) and 2080 to 2099 (right). Stippling is omitted for clarity (see text). Anomalies are relative to the average of the period 1980 to 1999. Results for individual models can be seen in the Supplementary Material for this chapter.*

Summary of Model Predictions

- Globally averaged surface T will increase by 1.8 to 4.0°C from 1980-1999 to 2090-2099.
- For the next two decades, a warming of about 0.2°C per decade is projected.
  - → Even if concentrations of GHGs and aerosols were kept constant at 2000 levels, a warming of ~0.1°C per decade would be expected.
- There are many other predictions in the IPCC report regarding:
  - → snow cover, sea ice, ice sheets, extreme weather, frequency and intensity of hurricanes, precipitation, circulation in the oceans,

Climate Change – The Response

- Scientific evidence of human interference with the climate first emerged in the international public arena in 1979 at the First World Climate Conference.
- In 1988 the United Nations General Assembly adopted resolution 43/53, proposed by the Government of Malta, urging:

  "… protection of global climate for present and future generations of mankind."
- The United Nations and its member states have been engaged in action to deal with the issue of Climate Change at a global level.
- In 1992, most countries joined an international treaty: the United Nations Framework Convention on Climate Change (UNFCCC), to begin to consider what could be done to reduce global warming and to cope with whatever impacts result.

The Kyoto Protocol

- The Kyoto Protocol is an addition to the UNFCCC treaty that commits countries to reduce their GHG emissions, and allows trading of pollution credits given that the impact on the global atmosphere will be the same.
  - →The text was adopted in 1997; it entered into force in 2005.
  - →Have a look: http://unfccc.int/kyoto_protocol/items/2830.php
- *"Depending on who you talk to, the Kyoto Protocol is either*
  a) an expensive, bureaucratic solution to fix a problem that may not even exist; or
  b) the last, best chance to save the world from the "time bomb" of global warming."
  (CBC - http://www.cbc.ca/news/background/kyoto/index.html)
- These are the extreme positions in the worldwide debate between governments, consumers, environmental groups, scientists, industry.
- A fundamental question is the level of confidence we have in our knowledge of what controls Earth's climate and what changes will happen in the future.

Canada and Climate Change

- As a northern nation, Canada is expected to experience a greater degree of warming than countries closer to the equator.
- Canada's average annual temperature has been increasing over the past century, and it may be more than 4°C warmer by the end of the next century (compared to the projected global average increase of about 2°C).
- For comparison, average global temperatures during the last ice age were only about 4 to 8°C lower than they are today.

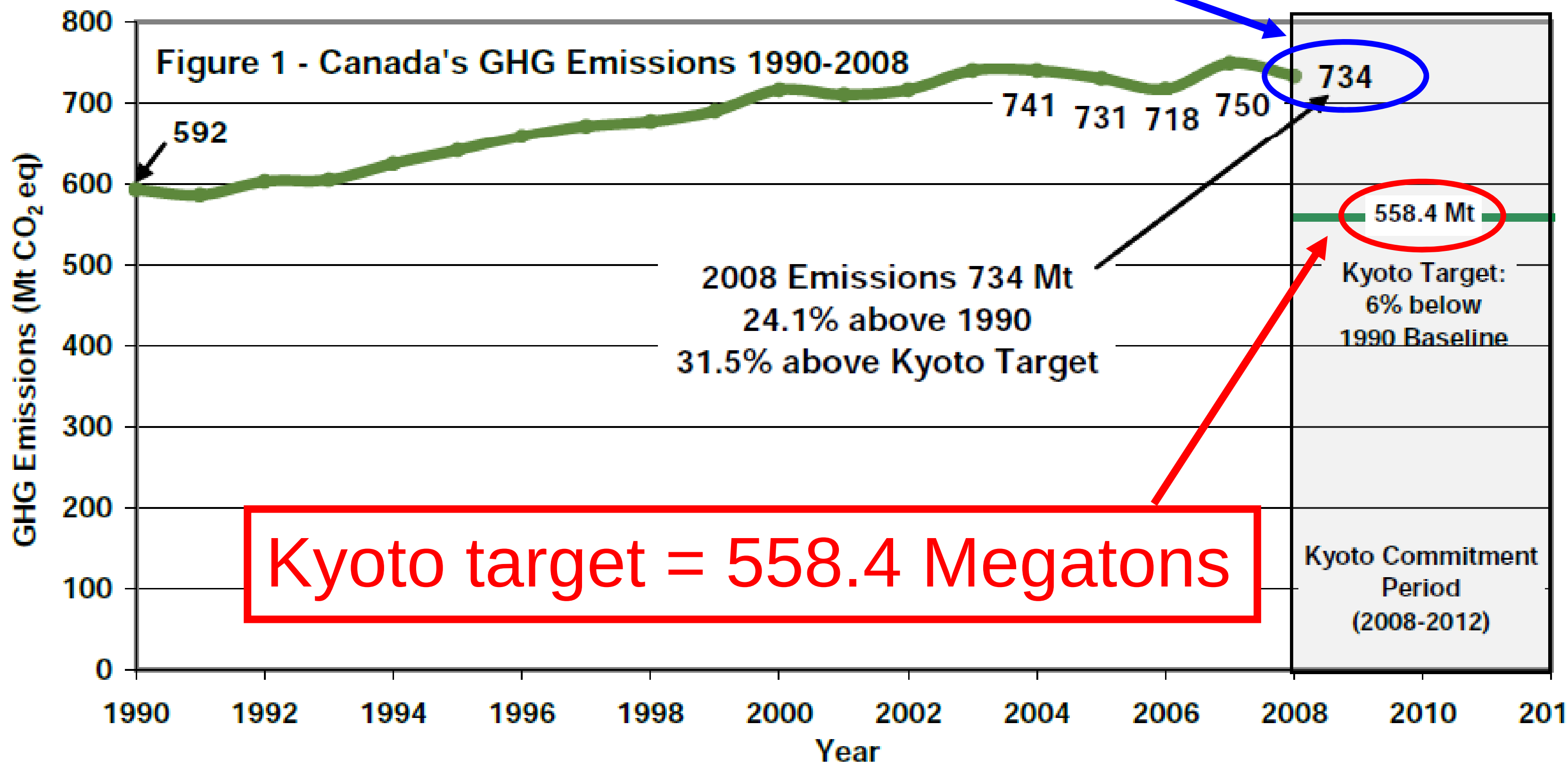
See the Arctic Climate Impact Assessment (2004)
http://www.acia.uaf.edu/

Canada's GHG Trends

Canada—National Inventory Report 1990–2008—Part I

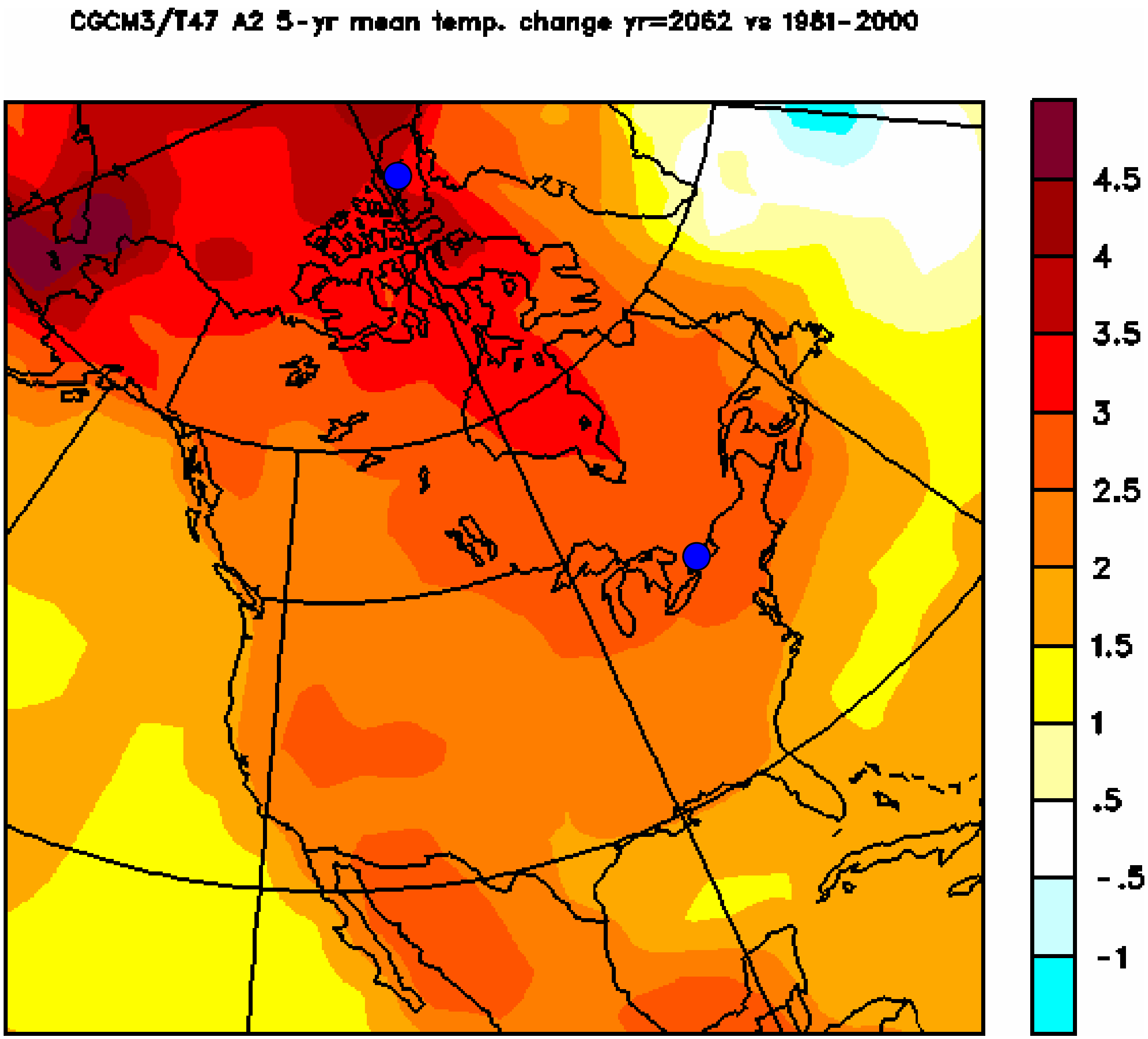
2008 emissions were 734 Megatons, 24.1% above 1990 levels and 31.5% above Kyoto target

Figure S–1 Canadian GHG Emission Trend and Kyoto Target



http://www.ec.gc.ca/Publications/default.asp?lang=En&xml=492D914C-2EAB-47AB-A045-C62B2CDACC29

Model Simulations for Canada



North American temperatures for 2000-2100, relative to the 1981-2000 average, simulated by the Canadian Global Climate Model (CGCM3)

See http://www.ec.gc.ca/cc/

http://www.ec.gc.ca/sc-cs/default.asp?lang=En&n=0EC06FB9-1#top

Concluding Thoughts

This is a very complex issue.

- **Scientifically**
  - → The case is still being made
  - → By the time it is conclusive, it may be too late
- **Politically**
  - → Politics is a very messy business
  - → The media likes an argument - often a disservice to the science
- **Economically and Ethically**
  - → How well do we need to understand the issue before acting?
  - → What will we give up for a benefit that we cannot see?
  - → Should we employ the "Precautionary Principle"? *("Scientific uncertainty should not be a reason to postpone measures to prevent harm.")*